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SHAKING A ROCKET TO DEATH

DR. BERNARD T. WOLFSON, Directorate of Engineering Sciences, AFOSR

The occurrence of destructive combustion pressure oscillations is frequently responsible for the failure of a rocket system through burnout or physical rupture of the combustion-chamber wall or other parts of the rocket engine. This is due to the excessively high temperatures, pressures and rates of heat transfer to the injector face and walls of the thrust chamber and nozzle which accompany this phenomenon. In addition, even if complete destruction of the rocket does not occur, combustion instability can play havoc with sensitive control and servo systems which are not designed to accommodate the violent mechanical vibrations which also occur.

In order to improve understanding of the fundamental processes of combustion instability, to provide realistic criteria for a priori design of new rocket motors, and to eliminate as much as possible the expensive cut-and-try methods frequently employed in rocket development, AFOSR has supported for a number of years research efforts in various aspects of the complex phenomenon of unstable rocket combustion. One important phase of this work involving the investigation of various mechanisms which can act to initiate or trigger and sustain rocket combustion instability has the express purpose of obtaining better fundamental understanding of this phenomenon.

Toward this end, under AFOSR sponsorship, a small group of scientists headed by Professor Percival D. McCormack, formerly at Trinity College, Dublin, Ireland and now at the Thayer School of Engineering Sciences, Dartmouth College, has been carrying out a comprehensive investigation (1-3) of the effect of severe mechanical vibration of the injector plate on liquid and gas fuel jets. Their main interest in this investigation lies in the possibility of this mechanism's acting to initiate high-frequency combustion instability in the rocket engine -- either on the ground test stand or in flight.

The sensitivity of jets, gas or liquid, to mechanical vibration of the orifice is an area to which very little attention has been given since the days of Lord Rayleigh around the end of the last century. This is surprising in view of the prevalence of vibration in mechanical systems and in view of the possible effect on combustion or fluid jet amplifier operation.

In the case of a laminar liquid jet, Professor McCormack found that -- provided the wave length of the disturbance on the jet is

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less than the circumference of the jet -- transverse vibration of the (circular) orifice can drive instability of the capillary type, first analyzed by Rayleigh (4) and then by Weber (5). In fact, Professor McCormack was able for the first time to check the validity of the Rayleigh-Weber theory. Within the context of first-order disturbance amplitude, he found that the theory accurately described this type of instability.

The phenomenon of plate or disc formation on a mercury jet had been demonstrated by J. Hartman in Denmark around 1933. He modulated the jet velocity electromagnetically, and the liquid "bunching" that ensued produced remarkable discs. By applying vibration with extremely high "g" values (over 200), Professor McCormack was able to produce similar disc formation on laminar liquid jets. The discs were not so large as

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From the Editor:

The July 1966 Review carried an article by Captain John F. Schaefer of FJSRL entitled "Control of Unstable Mechanical Systems." This article referred to an experimental study conducted by Captain Schaefer at FJSRL's Aerospace Mechanics Division. Actually, the experimental study and much of the theoretical work discussed in the article were conducted by Captain Schaefer at Stanford University. Since coming to the Aerospace Mechanics Division, FJSRL, Captain Schaefer has continued his research in the control of unstable systems, has obtained further computer verification of his original theories, and has written papers on them for publication.

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those obtained by Hartman, but were very pronounced. They suffered by being subject to atmospheric shattering and bending of the liquid around the edges of the discs. The only explanation for this phenomenon is that the vibration was causing modulation of the jet velocity at the injector. This mechanism at low "g" values acts as a trigger for the capillary-type instability, satisfying the rationally symmetric criterion laid down by Rayleigh.

In the case of a high-velocity atomized jet, Professor McCormack and his colleagues have shown that, while the capillary-type instability has no meaning in this context, high "g" vibration still induces velocity modulation and the mass concentration in the spray varies periodically at the applied vibration frequency.

Work on gas jets has revealed an interesting analogy with liquid jets. At low vibration acceleration values, provided the frequency is correct, vortex shedding can be driven. At high acceleration values, vortex shedding can be driven at any frequency. In either case the result is a considerably augmented rate of mixing. A fluid-jet classical closed solution for the case of mixing in the presence of a periodic source of vorticity at the orifice has been obtained and will be published shortly. Besides its direct significance in the field of combustion, a thorough investigation of this phenomenon can throw considerable light on the transition to turbulence from laminar flow.

The implications of Professor McCormack's research in the combustion-instability area have already turned out to be quite significant. The results obtained recently enabled one of the prominent rocket-engine manufacturers to diagnose quickly and eliminate an unanticipated instability during the development of one of the Lunar-Excursion-Module engines. ★

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RECENT CONTRIBUTIONS TO NONLINEAR ELLIPTIC EQUATIONS

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The theory of elliptic partial differential equations can be divided into two main areas. The first area deals with linear problems. The second area, more closely associated with physical reality, deals with nonlinear problems. Nonlinear equations give a more accurate mathematical representation of the world we live in than do their linear counterparts. However, they are incomparably more difficult to solve. At present there are many powerful tools and penetrating theorems for dealing with nonlinear equations, yet we are nowhere close to formulating a general theory.

Today the theory of nonlinear elliptic equations is a collection of results, methods, ideas, and points of view. Recent contributions to this steadily growing store of knowledge on nonlinear theory were presented at the American Mathematical Society's symposium entitled "Applications of Nonlinear Partial Differential Equations in Mathematical Physics," (1) jointly supported by the Army Research Office and the Mathematics Division of AFOSR.

It is now well established that the extremals of multiple integral variational problems of a suitable form are the solutions of

a particular class of nonlinear elliptic equations. Also, existence and differentiability of solutions of this class of equations has recently been brought to a certain degree of completeness. Very little effort, however, has been spent in determining the type of singularities which solutions may have.

One of the significant contributions on this subject was presented at the symposium by Professor James Serrin of the University of Minnesota, a principal investigator in a research program supported by the Mathematics Division of AFOSR. Professor Serrin's paper, entitled "Singularities of Solutions of Nonlinear Equations," deals with the behavior of solutions of nonlinear elliptic equations near isolated singularities. The main theorem of Serrin's paper states conditions under which the solution to the equation in a suitable domain has a removable singularity at the origin. A corresponding treatment of the behavior of a positive solution defined in an exterior domain is also included.

Another similar and significant contribution to the theory of nonlinear elliptic differential equations is contained in a joint paper (2) by Professor P. Hartman of the Johns Hopkins University and Professor G. Stampacchia of the University of Pisa, Italy. The authors obtain existence and uniqueness theorems for (weak) uniformly Lipschitz continuous solutions of Dirichlet boundary-value problems associated with a class of nonlinear elliptic differential-functional equations. Existence theorems for the solutions of certain nonlinear functional inequalities are also established, and a priori estimates for quasi solutions are developed. One of the novel features of the results of the paper is the fact that the equations considered involve nonlinear functionals rather than functions of the unknown function. ★

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LARGE SINGLE CRYSTALS OF SELENIUM

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There will be few readers of this article who do not realize that the science of single-crystal preparation is one of the mainstays of our materials-research effort. Our present-day electronics and space technology, with its spectrum of semiconductor products, depends ultimately upon the preparation of single-crystal semiconducting material. The development of single-crystal preparation from an art into a science has been a long and difficult process for, like the Pilgrim's way, the path of crystal growth has been beset with a wide variety of difficulties. Many of the problems are common to all crystals: dislocations, lineage boundaries, impurity fluctuations and the like. The means of circumventing these are usually similar, at least within a given family of materials. For example, the reduction of thermal gradients during cooling of a grown crystal is always beneficial, and homogenization of the growth medium ahead of the solid interface is a common practice. The challenge of crystal growth is always greatest when these problems are first encountered, for then the task appears as an intrinsic property specific to the crystal being grown. At this stage the demands may be more than science alone can meet, and one looks to the art of crystal growth for the initial solution.

AFOSR has recently cosponsored a research program with Westinghouse Research Laboratories, part of which included a study of the crystallization of selenium, an elemental semiconductor which fails to grow at adequate rates under conventional laboratory conditions. The selenium molecule in the liquid has polymer-like properties and, whatever the method of crystallization, the experimentalist must deal with the fact that the molecules in the medium ahead of the crystal may be in the form of chains of varying

lengths and varying degrees of kinkiness, or in the form of closed rings of eight Se atoms. In order to grow a single crystal, the interface must be able to select the appropriate molecular-entity length from this mélange. At room temperature the selection process is sluggish and the crystal growth slow, whatever the means. The purpose of the research was to develop a means of growing really large selenium crystals at reasonable rates, and to make these available for study. For selenium is, at present, one of the least-known elemental semiconductors.

Prior to the work at Westinghouse Research Laboratories, the largest selenium crystals that had been grown were 1.5 x .7 x .6 cm over all, in the form of imperfect hoppers. These were prepared by the Russian investigator, P. T. Kozgrev (1), from the vapor phase, taking two months to grow to this size. Because of the long time of growth and the poor habit, Kozgrev turned to melt growth. At one atmosphere, selenium melts at about 217° C; but the liquid is a glass-former and may be readily undercooled several degrees below the melting point without any visible sign of nucleation. If the undercooled liquid does nucleate, or if it is deliberately seeded, the growth rate of the resulting solid is exceedingly slow. Kozgrev found that, to control melt growth, he had to allow it to proceed at the same rate as the vapor process, about a quarter of a millimeter a day. Even at this low rate he was unable to obtain single-crystal ingots, although occasionally large grains could be separated from the solidified mass. The difficulty in this procedure is that selenium is very susceptible to mechanical damage, slipping readily on the $\{10\bar{1}2\}$ planes. From the sluggish rate of melt growth, Kozgrev rightly deduced that the limitation lay in the nature of the molecular configuration presented for attachment to the freezing interface. Nasledov and Kozgrev (2) then tried to grow selenium under pressure, to take advantage of the increase in the freezing point with increasing pressure. They reasoned that, with increasing temperature, the probability of finding the correct molecular configuration in the liquid would increase, and obtained polycrystalline ingots with a maximum grain size of about 0.5 cm in diameter. These still had to be pried or cut loose from the mass, and were so damaged that little meaningful data could be obtained from them. The crystal growth rate was some three orders of magnitude higher than that experienced at atmospheric pressure, thus providing the first insight into the means of accelerating the growth of this elemental semiconductor.

The culminating step in this story was the production of single crystals of selenium, 1 cm in diameter and 10 cm long, at Westinghouse under the cosponsorship of AFOSR. For atmospheric pressures, it is experimentally not too difficult to make the transition from a polycrystalline ingot to single-crystal growth. The furnace is adjusted to have gentle temperature gradients, and the ingot mold is made with a tapered end so that a single grain may predominate over the many that are initiated there. The optimum rate of normal freeze is then determined. The final important condition in the growth of the resulting single grain is that the interface remain more or less planar, and that supercooling be avoided in the liquid. If supercooling does occur, stray grains nucleate ahead of the interface, either in the body of the melt or in the walls of the container. To grow selenium, these same criteria had to be met, not at 1 but at 5,000 atmospheres pressure.

Fig. 1 shows the apparatus developed by Dr. D. E. Harrison and W. A. Tiller (3) for the growth of large crystals. Selenium was contained in an open quartz vial within a Stellite pressure bomb. The system was pressurized by pumping argon at 2,000 kbar into this bomb (and a second bomb, not shown) which was cooled to liquid-nitrogen temperatures to liquify the argon. The second bomb was then warmed to evaporate the argon, driving the pressure to its operating value and maintaining it there for the duration of the experiment. During this time, heaters (B-B') and a water-cooled quench tank (C)

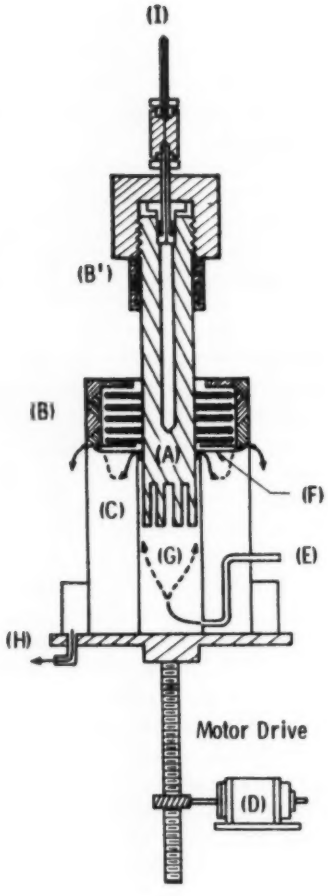

Fig. 1. Apparatus for melt-growth of selenium single crystals under high pressure.

The Stellite bomb (A), which contains selenium in a quartz tube, is subjected to 5,000 atmospheres argon pressure through inlet (I). Heaters B and B' raise the selenium temperature above its melting point; then a controlled temperature gradient is passed through the molten sample, causing it to solidify. The combination of fins on (A), heater (B) and water bath (C, E, F, G and H) produces a thermal gradient of ~45° C/cm. The gradient is moved by drive motor (D) lifting (B, C, G) upward around fixed bomb (A). Under these conditions, crystals of selenium about 1 centimeter in diameter and 10 centimeters long can be grown at 0.15 to 0.4 cm/hr.

were moved slowly up the first bomb. These initially carried a constant temperature zone, some 30° C above the melting point, through the selenium, melting the sample. This was followed by a region in which the temperature dropped about 45° C/cm. The rate of growth was typically 10^{-5} cm/sec, with the growth front essentially planar.

Fig. 2 shows large ingots of single-crystal selenium. For the top ingot, initial growth was from the tapered end and was polycrystalline; but single-crystal growth prevailed over the bulk of the ingot. The growth direction was 10 to 40 degrees off the rhombohedral "c" axis, and detailed observations have shown that a certain amount of lineage structure is present. Although X-ray rotation photographs about the "c" axis gave well-defined layer spots, "a" axis rotation showed considerable (4) streaking. The small pits on the sides of the ingots were caused by bubbles of the high-pressure medium, argon. The selenium melt was outgassed prior to each experiment to avoid other extraneous bubbling. There seems to be little question but that the success of this process can be ascribed to the very careful control of the thermal environment. These crystals have been made widely available, and it is expected that we shall soon see a considerable number of papers in the literature on their properties.

There remains, then, the basic problem of the marked increase in the rate of solidification as the pressure and temperature are raised. The theory of Eisenberg and Tobolsky (5) describes the structure of the liquid by considering the reversible reaction involving the breaking of the 8-atom selenium rings and the attachment of ring material onto chains. Since this ring-chain equilibrium can be related to viscosity, Harrison was able to deduce the average chain length from pressure-viscosity data taken in a novel high-pressure viscometer. (6) He found that the average chain length near the melting point is about 800 units of Se_8, while at 342° C the chain length is nearer 100 of these units. Now, the viscosity of the melt falls with increasing temperature. At constant temperature, the viscosity rises with pressure, but at such a rate that the net viscosity at the

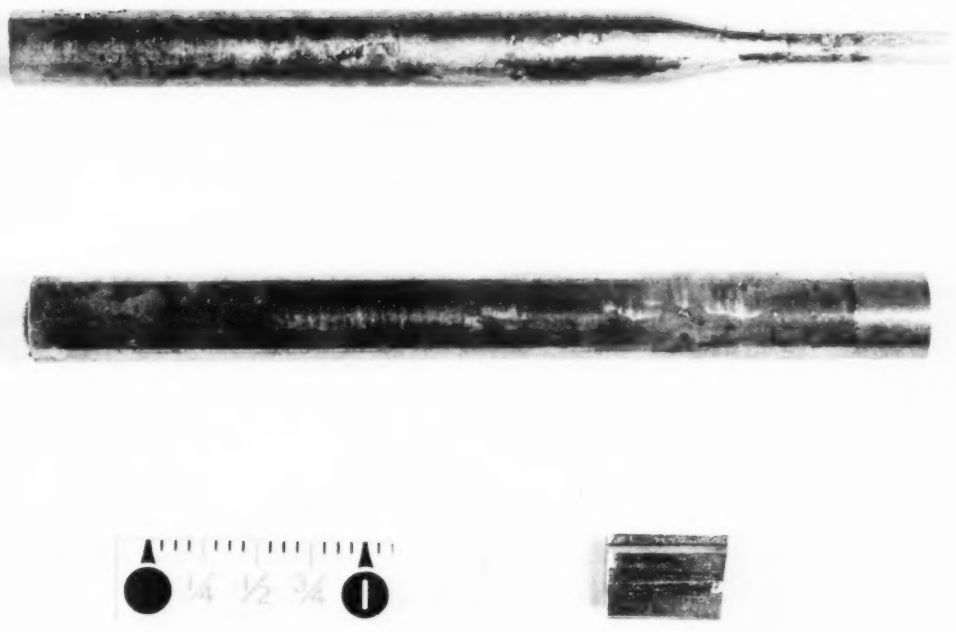

Fig. 2. Large crystals of selenium. The two top crystals have been grown parallel to the "c" axis, the topmost crystal from a subdiameter seed, and the middle crystal from a full-diameter seed. Note the whiskers (needle-like crystals) at the left end of the middle crystal (top end during growth). A section which has been cut from a crystal and cleaved parallel to the "c" axis appears with the inch-scale marker.

freezing point decreases with higher pressures and temperatures. Since the ring-chain equilibrium and chain length are but little affected by pressure, the selenium melt in these growth experiments is not only more fluid at 342° C, but also has simpler, shorter chains than selenium liquid at its melting temperature at ambient pressure. Crystallization is thus faster.

The selenium melt, with its ring-chain equilibrium, is essentially polymeric in character; in common with other polymer melts, selenium may crystallize as spherulites at atmospheric pressure. This spherulitic growth may be entirely suppressed at high pressures. It thus seems likely that a pressure variable may be useful in obtaining crystals of other materials with polymeric melts. Polyethylene, for example, may be a possible candidate. Single crystals of polyethylene may be grown from solution; but their size is such that they must be examined in the electron microscope. Their dimensions are thought to be related to a chain-folding process occurring in attachment to the solid, the chain-folding length determining the thickness of the lamellae that form the basic structural unit of these tiny crystals. Westinghouse has recently attempted to crystallize polyethylene in the high-pressure apparatus. A transition from spherulitic to extended grain growth has been observed, suggesting that the freezing process has been substantially altered. Of course, the chain length in polyethylene and related compounds is considerably greater than that of selenium, and the problem of growing large single organic polymer crystals is

thus much more formidable; but it does appear that the use of elevated pressures is a step in the right direction. Polymer crystals would be widely welcomed for they would make possible the determination of accurate bulk properties, quantities which at present are not known with any precision.

Crystal growth from the melt at high pressures is still in the very early stages of development. Although it is tempting to speculate on the possibilities, we must, as always, await the outcome of our experiments. Nevertheless, the achievement of the Westinghouse researchers in the field of crystal growth and of solid-liquid kinetics is a signal demonstration of progress in 15 years of growing semiconductor crystals by well-established techniques. Solid-state scientists concerned with basic structure-sensitive properties of materials now have pure single crystals of ample size on which they can perform reproducible experiments and controlled measurements of the electronic structure and the semiconducting properties of selenium. ★

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APPLICATION OF THE DIFFERENTIAL INTERFEROMETER TO ARC-HEATED PLASMAS

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The major problem associated with the evaluation of energy-exchange processes in plasma-flow systems is obtaining detailed information on the state of the plasma and its surroundings. The desired information may include temperature and particle-density distributions as functions of space and time. Although laser and Mach-Zender interferometers are available, these instruments are expensive and require considerable effort to set up. In addition, the laser-type interferometer requires lateral scans and stable operation of the plasma system for long periods of time. Because many engineering plasmas are time-dependent, temporal as well as spatially resolved measurements are required. For these reasons, an in-house experiment, in conjunction with the Physics Department of the Air Force Institute of Technology, was initiated to study the applicability of the differential interferometer to plasma diagnostics. (1)

The interferometer developed was constructed from component parts, and is much less expensive than a Mach-Zender interferometer. In addition, setup and alignment may be accomplished in a very short time, usually several hours. A simplified optical diagram of the interferometer is shown in Figure 1. In operation, rays from a high-pressure mercury source are plane-polarized and focused on Wollaston prism 1. As shown for the sample ray in the diagram, this prism, when properly oriented, splits an incident ray into two diverging rays of equal intensity with electric-field vectors at right angles to each other (see Reference 2). A spherical mirror, located very near the arc plasma, focuses the two rays back on Wollaston prism 1 which lies at the mirror's center of curvature. The two rays emerge as a single ray with a difference in phase of the E vectors. This difference in phase, combined with the lateral distance (Δx) between the two rays as they pass through the plasma, gives a measure of the lateral gradient in the optical path of the plasma source. This information is sufficient to determine the index of refraction as a function of the arc radius. This is explained in

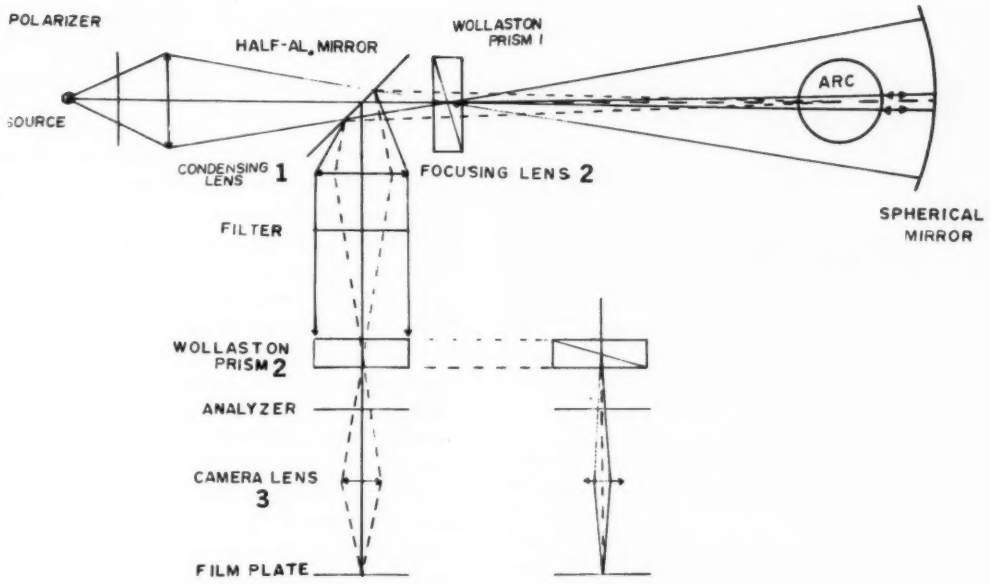

Fig. 1. Schematic of the Wollaston Prism Differential Interferometer.

more detail in Reference (1).

In order to measure the phase difference in the E vectors, a second Wollaston prism and analyzer are used. A half-aluminized mirror and lens 2 focus the emerging rays from prism 1 parallel to the optical axis so that they are incident perpendicular to the surface of prism 2. Prism 2 is oriented so that the two emerging rays corresponding to each incident ray lie in a plane perpendicular to the plane of Figure 1. These rays, after passing through a narrow band-pass filter (8Å half-width) and analyzer, are focused by lens 3 along with the arc image on a screen or photographic plate where they interfere. At this plane, a fringe pattern is formed. With no plasma present, a series of horizontal fringes is observed. The details of the formation of this fringe pattern may be found in Reference 2. With a plasma or other object, the fringes shift in the vertical direction; the vertical displacement is a measure of lateral gradient in the optical path through the plasma.

The combined accuracy of the interferometer and data-reduction technique was determined by using an axially symmetric helium object near room temperature. The symmetric helium object was obtained by flowing helium from a 1-inch-diameter tube into room air. Steel wool in the tube served to straighten the flow after the helium had passed through a copper coil immersed in a water bath maintained at room temperature. The resultant fringe pattern is shown in Figure 2, and the reduced data (index of refraction minus one) obtained by using a computer code based on the Nestor-Olsen method of solving the Abel-type integral equation is shown in Figure 3 (Reference 3). The published value for the helium index of refraction is 1.0000319, while the measured value obtained ranged from 1.000031 to 1.000033. Thus, for a steady source, one may expect to measure indices of refraction with an error of approximately $\pm 10^{-6}$. These data show that the differential interferometer is a reliable instrument for measuring indices of refraction for axially symmetric objects.

Following the helium measurements, the radial distribution of the refractive index of an arc-heated argon plasma was measured at a single wave length. In addition, the tempera-

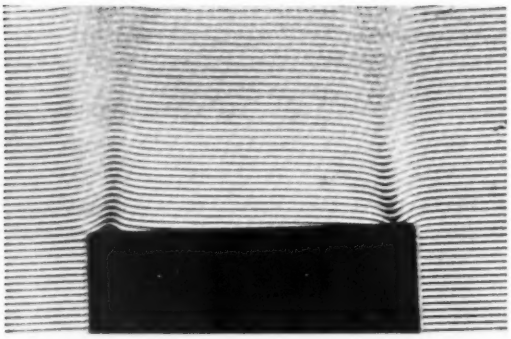

Fig. 2. Interferogram of room-temperature helium flowing into air.

ture distribution in the argon arc was determined from the measured radial distribution of the continuum radiation. A comparison of the results, based on a reference temperature of 8,800° K, is shown in Figure 4. The calculated curve in Figure 4 is based on the contributions to the refractive index by ground-state atoms and ions and free electrons. The effects caused by the lowering of the ionization potential and the excited-state atoms were not considered in the calculations. However, calculations based on known argon transition probabilities indicate that the effects of the excited states are probably

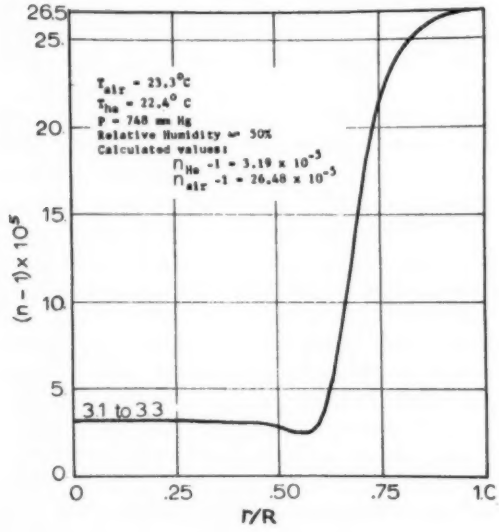

Fig. 3. Measured refractive index of helium.

smaller by two orders of magnitude for the temperature range investigated. The results obtained confirm the assumptions used in the calculations.

In addition to checking dispersion theory, the interferometer may be used as a diagnostic tool. The results indicate that electron densities greater than 10^{16} electron/cm^3 may be measured if 2 wave lengths are used with 1 wave length in the near-infrared. Also, the interferometer provides an excellent technique to measure the temperature and number density distribution from 8,000°K to room temperature. This is important for some applications because the lower limit of spectrometric measurements is approximately 8,000° K.

Future plans include making a more detailed study of arc-heated argon and helium plasmas by using a number of narrow-band filters at different wave lengths as well as testing the feasibility of using the differential interferometer in conjunction with a spectrometer to measure the dispersion of spectral lines as a function of wave length. ★

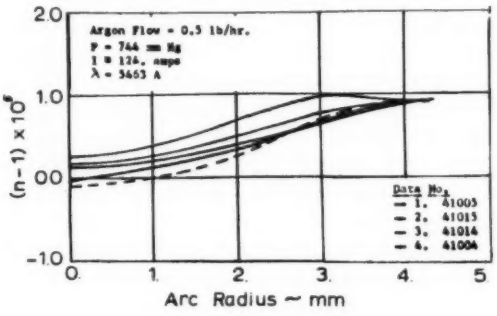

Fig. 4. Measured and predicted refractivity of the arc core.
Dashed curve is the theoretical prediction based upon temperature measurement.

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PHONETIC THEORY

OFFICE OF THE ASSISTANT EXECUTIVE DIRECTOR, AFOSR*

For a number of years, AFOSR has been supporting work on phonetics and acoustics by Drs. Gordon E. Peterson and June E. Shoup at the University of Michigan. A great deal of important research has flowed from this work. In the March 1966 issue of the Journal of Speech and Hearing Research (JSHR), Drs. Peterson and Shoup published a group of three articles, summarizing their work to date. These were "A Physiological Theory of Phonetics," "The Elements of an Acoustic Phonetic Theory," and "Glossary of Terms from the Physiological and Acoustic Phonetic Theories."

To describe the significance of these articles, the Chairman of the Publications Board of JSHR, Dr. Paul Moore of the Department of Speech, University of Florida, wrote a foreword which is reprinted below with the permission of both Dr. Moore and JSHR.

FOREWORD

"Histories of the sciences and academic disciplines contain numerous examples of discoveries and theoretical functions that have become recognized as reference points in the development of the field to which they belong. Sometimes these events lie dormant until later findings reveal their significance; sometimes they gradually infiltrate the field; and sometimes they are heralded at their inception for their recognized potential contribution and are put to use immediately. It is my opinion that the phonetic theories presented in this issue by Peterson and Shoup add significantly to the essential knowledge of all fields concerned with oral communication, and that they should be specifically recognized for their potential worth to the membership of ASHA (American Speech and Hearing Association). It is probable that the combined presentation of 'A Physiological Theory of Phonetics' and 'The Elements of an Acoustic Theory of Phonetics' with their associated 'Glossary of Terms' will constitute an important theoretical and practical phonetic milepost. It seems both appropriate and mandatory that they be published together and made available to the entire membership.

"The 'Physiological Theory of Phonetics' incorporates much that has withstood the tests of time, and amalgamates that information with newer concepts that have come from recent research and investigations. The physiological parameters of descriptive phonetics have been recast within the concepts of modern linquistics to form a consistent theory that can serve as a base for instruction and research. The presentation is detailed and meticulously complete; it relates theoretically to all probable language sounds and to their production. It is not easy reading, but it is essential reading and forms a background for the meaningful study of the acoustic theory set forth in the second article.

"Acoustic theories of phonetics as well as physiological theories have been available for various purposes for a long time; but, as the authors point out, the relationships between these two approaches have not been closely drawn and, in fact, have not been clearly identified. The philosophy of the writers concerning the distribution of the acoustic theory and its relationship to the physiological information is clearly revealed in the following statement from the second article. 'It is hoped that this

*Contributed by Major Joseph P. Martino, AFOSR.

present paper will show the extent to which the acoustical characteristics of speech can be used as a basis for descriptive phonetics. In this sense the paper is concerned with the essential properties of a general acoustic phonetic theory. Such a theory is needed for many purposes, but it cannot stand independently of a physiological phonetic theory. In fact, a physiological theory must provide the basic reference for an acoustic phonetic theory. As the following pages suggest, it is not likely that an acoustic phonetic theory can be constructed independently, without reference to physiological phonetics.'

"The simultaneous presentation of two distinct but related papers enables the authors to focus separately upon the unique features of the physiological and acoustics concepts, and concurrently to indicate the interrelationships that exist. There can be little doubt that the availability of both papers within the same issue not only increases understanding, but will also enhance the usefulness of the theories.

"It is hoped that this publication will constitute a significant service to the membership." ★

ionizing shock waves in an electromagnetic shock tube

MAJOR RUSSELL G. LANGLOIS
Directorate of Engineering Sciences, AFOSR

The propagation of waves in gases has been studied as early as the mid-19th century by Stokes and Challis. They learned that sound waves or acoustic waves propagate at a characteristic velocity, and can be described as a small disturbance in a compressible fluid. As the amplitude of the disturbance becomes large, the wave front becomes steep, and the simple theory breaks down. A discontinuity appears between the flow conditions upstream and those downstream. This discontinuity is called a shock wave, and has been studied extensively by authors too numerous to mention. Because of their relevance to blast effects and the design of aircraft and spacecraft, shock-wave phenomena up to hypersonic speeds have been thoroughly investigated. This leads us from the developments in what might be called classical shock waves to a new kind called the strong ionizing shock wave.

Since a shock wave is the transition area between two vastly differing regions in space, it can be expected that, as its speed increases, major physical changes will occur across the shock front itself. The shock front is the region of very steep temperature gradients separating the cold gas (preshocked) from the hot gas (postshocked). It is usually a few mean free paths thick. As the Mach number increases, the temperature of the postshocked gas increases roughly as the square of the Mach number until about Mach 5. (See Fig. 1). Using hydrogen, dissociation begins at this point, and the hydrogen becomes 100% dissociated at speeds of Mach 20. At this latter Mach number ionization begins, and if the Mach number is increased further to Mach 56, the gas will consist only of electrons and protons. Increasing the Mach number still further will provide enough energy to the particles to produce nuclear reactions. About Mach 20, therefore, the gas becomes a conducting plasma; and it is here that electromagnetic (EM) effects become important. In the ordinary gas dynamic shock tube, pressure forces drive the shock front. In the EM shock tube, the ionized plasma may be considered as a conductor, and the shock is driven electromagnetically. (See Fig. 2) Two kinds of shock waves should be distinguished at this point. Shock waves that ionize the gas and make it a conductor as they pass through it are called "ionizing shock waves." Shock waves that propagate through a gas already ionized and conducting are called magnetohydrodynamic (MHD) waves.

Research sponsored by AFOSR at Columbia University has been centered on generating ionizing shocks using an electromagnetic

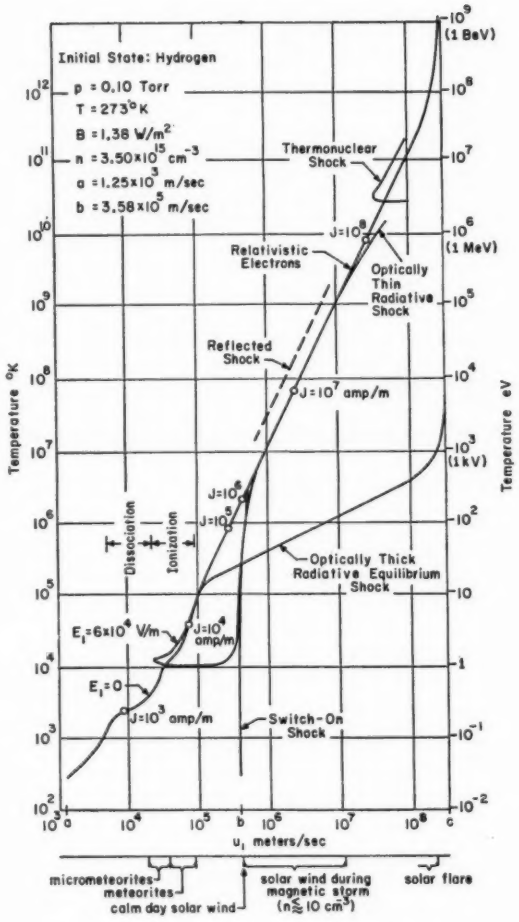

Fig. 1. A plot of temperature vs. shock speed.

shock tube. Professor Robert Gross, principal investigator, has found rather striking differences between ionizing shocks and MHD shocks. (1) One might expect that, with a dielectric medium in front and a highly conducting plasma behind, the ionizing shock-wave behavior would be a mixture of an ordinary gas dynamic shock (no conductivity on either side of the shock) and a pure magnetohydrodynamic shock (high electrical conductivity on both sides). This is not quite the case, since the electric field ahead of an ionizing shock influences the shock behavior markedly. The source of the electric field originates in the ionizing shock structure. In pursuing the theory further, four new features which distinguish ionizing shocks from MHD shocks were uncovered. These are:

a). For ionizing shocks, one cannot arbitrarily specify the preshock electric field.

b). The ionizing shock-wave solutions are bounded for a given electric field and, below a certain speed, there are no steady-state solutions.

c). The postionizing shock temperature is higher than the zero electric-field case.

d). Above a certain electric field, there is no steady solution for slow ionizing waves.

Professor Gross has also obtained switch-on shock behavior with ionizing waves at sub-Alfvénic speeds. A switch-on shock is one in which a magnetic field and a component of momentum, tangential to the flow direction, are generated by the shock. In MHD shocks, switch-on waves occur in the speed range greater than the Alfvén speed (characteristic velocity of an electromagnetic disturbance in a conducting gas). In recent experiments, Miller (2) of Columbia has clearly identified ionizing switch-on shock waves by means of magnetic-field probes. Under some conditions a uniform gas sample behind the shock has been obtained; however, there appears

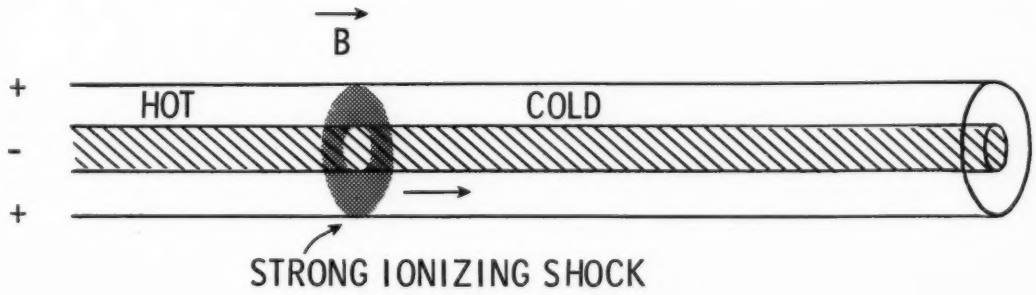

Fig. 2. An electromagnetic shock tube.

to be a considerable divergence in results among several investigators doing similar work.

Most of the research in high-temperature plasmas is motivated by controlled thermonuclear applications and aimed at solving astrophysical problems. The shock heating of plasmas to temperatures required for nuclear ignition appears to be a valid concept. However, much more research is required to understand the behavior of shock waves at these temperature regimes, where radiation and relativistic effects play an important role. ★

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(1) Gross, R. A., "Strong Ionizing Shock Waves," Review of Modem Physics, Vol. 37, Number 4, October 1965, pp. 724-743.

(2) Miller, B., "Ionizing Shock Studies in an Electromagnetically Driven Shock Tube," Columbia University, New York, AFOSR 66-0300, June 1965.

DETECTION AND IDENTIFICATION OF BACTERIA BY GAS CHROMATOGRAPHY

MAJOR MORTON REITMAN, USAFR, Life Sciences Division, Hq OAR*

In the event of a biological-warfare attack, a method of rapidly detecting and identifying viable micro-organisms in a background containing a large number of nonviable agents and nonbiological materials may prove to be very useful for defense measures. Under the sponsorship of AFOSR, a study to assess the feasibility of detecting and identifying bacteria by an investigation of their metabolic products was initiated in October 1964 by Dr. Y. Henis, Dr. M. Alexander and Mr. J. R. Gould of the General Electric Company.

The methodology employs the selectivity of the gas chromatograph in conjunction with ultrasensitive detectors, such as the electron-capture detector and the flame-ionization detector, for the analysis of gases, volatile products, or other products of metabolism that can be converted into volatile derivatives. Many volatile compounds are synthesized by micro-organisms during their growth. Through the use of sensitive instruments, the presence of small numbers of bacteria may be determined by detecting the formation of specific bacterial products. In addition, because of the sensitivity of certain detectors employed with the gas chromatograph, it may be possible to devise a method for the detection of as-yet-unknown unique compounds which might serve as an additional or rapid means for establishing the presence and classification of bacteria.

Excretory metabolities from growing cultures of bacteria have been analyzed by gas chromatographic methods, and chromatograms representing a signature or fingerprint for each bacterium have been obtained. These chromatograms could be used to distinguish the bacterial strains from one another simply by considering the presence or absence of peaks, or by the quantities of the various products formed.

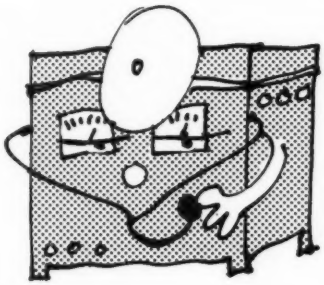
In order to facilitate identification of the volatile metabolites, a number of known products of bacterial metabolism were examined. Results suggest that it is possible to detect quantitatively as little as 22 picograms (1pg = 1 x 10^{-12} grams) of diacetyl and acetoin. E. coli, B. circulans, and B. megaterium, organisms classified as acetoin-negative, generated products which were identified by gas chromatography as diacetyl and acetoin. In view of the frequency of these two products in bacterial cultures and the extreme sensitivity of the electron-capture detection unit to them, one of the most effective methods for detecting the presence of micro-organisms might well be to examine for diacetyl and acetoin formation.

**Maj Reitman was on active duty at Hq OAR when he wrote this article.*

The results of this study indicate that this technique may not only be useful in determining the presence of small numbers of organisms by detecting the formation of specific products, but that such techniques may also have application in the clinical laboratory. A physician may no longer have to wait two to three days for a laboratory report on a causative disease agent, but may be able to obtain this important information in a matter of hours. ★

COMPUTER SELF-DIAGNOSIS

MAJOR JOSEPH P. MARTINO
Office of the Assistant Executive Director
AFOSR



In any computer system, it is vitally necessary to be able to determine whether or not the computer is functioning correctly. Failures in one or more elements may permit the computer to continue to operate but, by producing erroneous computations, make the results of that operation worthless. This can be of particular significance in computers used in aerospace vehicles for such functions as bombing and fire control, and for attitude and trajectory control. If a computation is in error, the result can be complete failure of the mission, or even loss of the vehicle. Thus, a rapid method of locating computer malfunctions, and of diagnosing the cause of these malfunctions, would be extremely valuable in improving the reliability and capability of computers used in aerospace applications.

The Co-ordinated Science Laboratory (CSL) of the University of Illinois, supported by the Electronics Division of AFOSR through the Joint Services Electronics Program, has been investigating the problem of computer self-diagnosis. Drs. E. Manning and D. Compton of that Laboratory have devised a procedure for self-diagnosis of digital computers, based on the CSX-1 computer developed at CSL. This procedure has been tested and shown feasible.

In operation, the self-diagnosis procedure consists of a short program which is loaded into the computer and started running. If the program runs to completion, this is a necessary and sufficient condition that there are no failures in the system (i.e., that if any element has failed, it has been supplanted by a redundant back-up element), and that therefore the computations of the computer are correct. In the event of a failure of the program to run to completion, a fault is present in the computer. The computer operator then determines the contents of the program registers of the computer (this is a simple print-out process), and consults a handbook which provides a manual procedure to be implemented on the computer. Execution of this manual procedure will permit diagnosis of the fault.

The procedure for self-diagnosis was tested by simulating the CSX-1 computer on a Control Data Corporation 1604 computer, with failures of some of the elements included in the simulation. (This was a simpler procedure than introducing genuine element failures in the CSX-1.) The experiments showed that self-diagnosis was feasible, and that the execution hardware could be checked in a fraction of a second, with at most a few minutes of additional time required for the fault-locating procedure if, in fact, the diagnosis showed that the computer was not fault-free. The techniques used for self-diagnosis and fault location appear to be applicable to a variety of computers; but, because of differences in hardware and design, each computer will require a different self-diagnosis program. Successful demonstration of the program on the CSX-1, however, provides considerable confidence that similar procedures can be devised for computers which will be used in aerospace vehicles. ★

PROFILES

Mr. Paul W. Schreiber, an ARL scientist with the Thermomechanics Research Laboratory, is currently doing research concerned with the application of experimental and theoretical plasma physics to electric arcs. This work includes developing experimental and analytical techniques to determine the special distributions of emitted radiation, absorbed radiation, temperature electron density, and ion density in alternating-current and direct-current arcs as a function of time. Mr. Schreiber has a B.S. from the University of Dayton (1950) and an M.S. from Ohio State University (1956). He has also completed 40 semester hours beyond the M.S. degree at the University of Cincinnati. He has a number of publications to his credit. In this issue of the Review, he discusses "Application of the Differential Interferometer to Arc-Heated Plasmas."

Dr. Robert N. Euwema, an ARL research physicist, is with the Solid State Physics Research Laboratory. Currently, he is making crystal field theory calculations in collaboration with the ARL high-pressure group headed by Dr. D. W. J. Langer. Also, he is carrying out an investigation of the energy band structure of II-VI compounds with Dr. T. Collins. Dr. Euwema has a B.S. from the Pennsylvania State University (1954), and an M.S. (1956) and Ph.D. (1959) from Princeton University. He was formerly an instructor at Princeton University, and an assistant professor at Swarthmore College. He has several publications to his credit. Dr. Euwema and Dr. Langer are co-authors of the article, "Low-Voltage Injection Luminescence in Zn Se:Mn," which appears this month in the Review.

Dr. Philip Lieberman, of the Speech Research Branch, Data Sciences Laboratory, AFCRL, has conceived and developed a "System for Detecting Ground Fire by Helicopter Pilot," described in this issue of the Review. He received his B.S. and S.M. degrees in Electrical Engineering (1958) and his Ph.D. in Linguistics (1966) from the Massachusetts Institute of Technology. Dr. Lieberman served as a lieutenant in the Air Force from 1958 to 1962, and has been associated with AFCRL since 1958. He is a member of the Linguistic Society of America and of the Accoustical Society of America. He was elected to Sigma Xi in 1958 and to the Technical Committee of Speech Communication of the Acoustical Society of America in 1963. Dr. Lieberman has published and presented more than 20 papers in the field of speech production, speech perception, and linguistics.

LOW-VOLTAGE INJECTION LUMINESCENCE IN ZnSe:Mn

DR. DIETRICH W. J. LANGER and DR. ROBERT N. EUWEMA, Solid State Physics Research Laboratory, ARL

Properties of manganese luminescence centers have been studied extensively in the past, but the major emphasis has been on powders in sulfide and silicate compounds. (1) The present report deals with some characteristics of Mn in a ZnSe single-crystal host lattice.

The spectral distribution of the luminescence of a 1% Mn sample at 4.2° K is shown in Fig. 1 An identical distribution is obtained from excitation either by UV light or current injection. At lower Mn concentration (<0.1%), structure can be detected at the short-wavelength edge of the emission band (Fig. 2). When considered in connection with corresponding absorption data (2) and in conjunction with similar but more pronounced data in ZnS:Mn, (3) this structure may be interpreted in terms of phonon-assisted transitions and zero-phonon transitions within the Mn^{++} ion, at a site of cubic symmetry. The resulting crystal field terms have been fitted by least squares to the centroids of the observed Mn absorption bands in ZnSe. The relevant constants thus can be derived and the best fit furnishes the values F_2 = 55454, F_4 = 34520, and Dq = 405 cm^{-1}. The Stokes shift between the $^4T_1 \rightarrow {}^6A_1$ zero-phonon line and the centroid of the emission is approximately 825 cm^{-1} in ZnSe.

Electrically, ZnSe:Mn (1%) shows a surprisingly low resistivity both at room

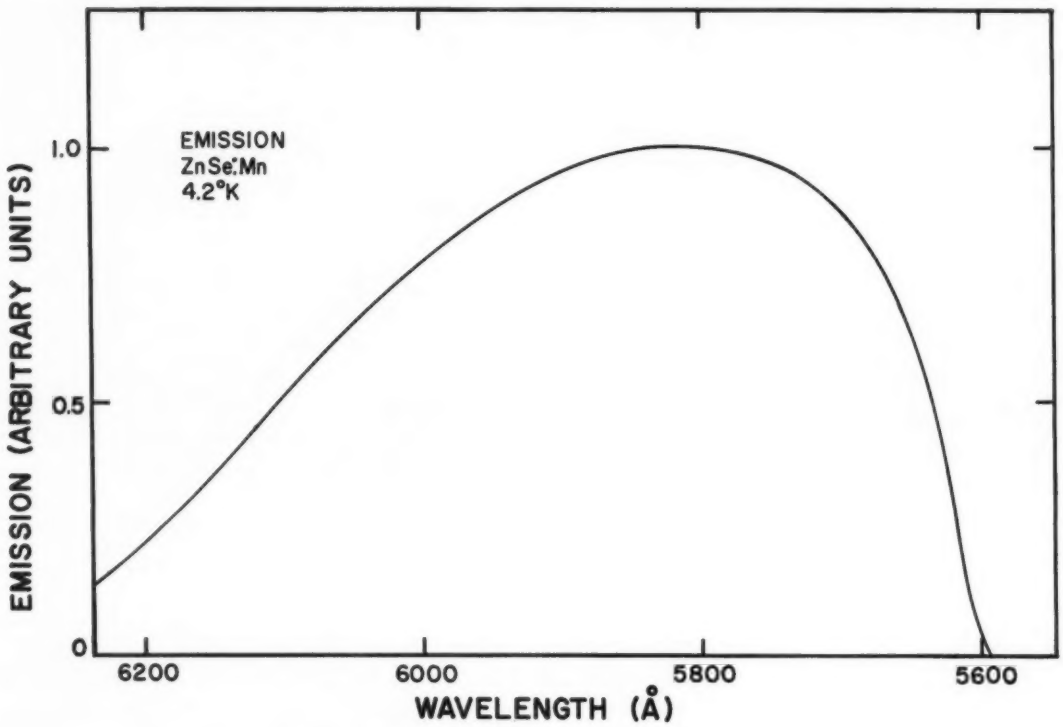


Fig. 1. Spectral distribution of the luminescence of ZnSe:Mn at 4.2° K.

temperature and at liquid-nitrogen temperature. This is probably due to the high deviation from stoichiometry usually observed in melt-grown crystals. The dashed line in Fig. 3 shows the voltage-current characteristic for a typical sample at 77°K, with the n-type contact made of indium and the p-type of silver epoxy. Measurements were made with pulses 10 to 300 μsec long to avoid excessive heating. Light emission with the

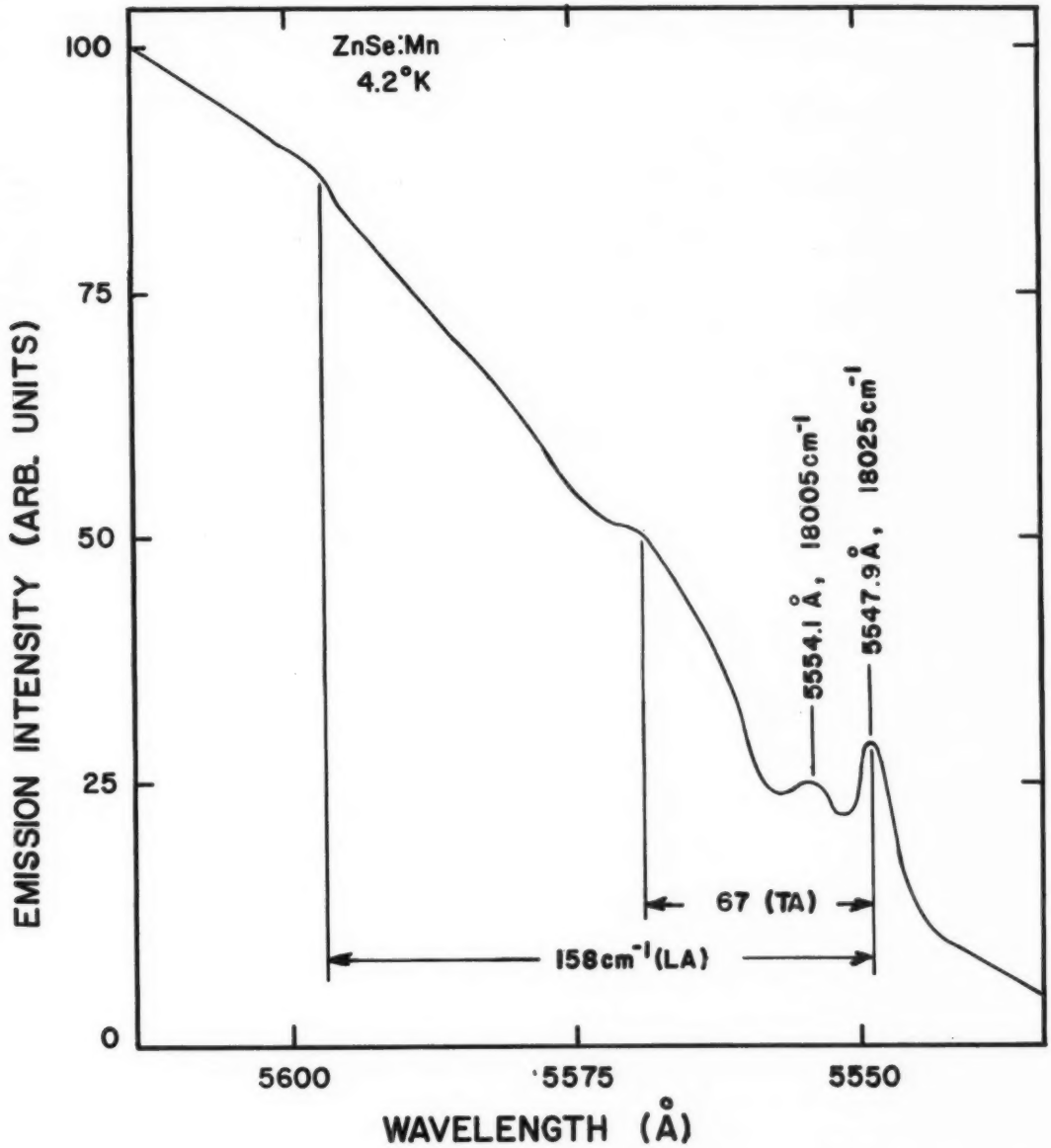


Fig. 2. The zero-phonon line corresponding to the $^4T_1 \rightarrow {}^6A_1$ transition in Mn^{++} at 18.025 cm^{-1} in ZnSe. The energy differences between this and other lines (TA = 67 and LA = 158 cm^{-1}) correspond to energies of the transverse acoustical (TA) and longitudinal acoustical (LA) lattice vibrations of the host lattice.

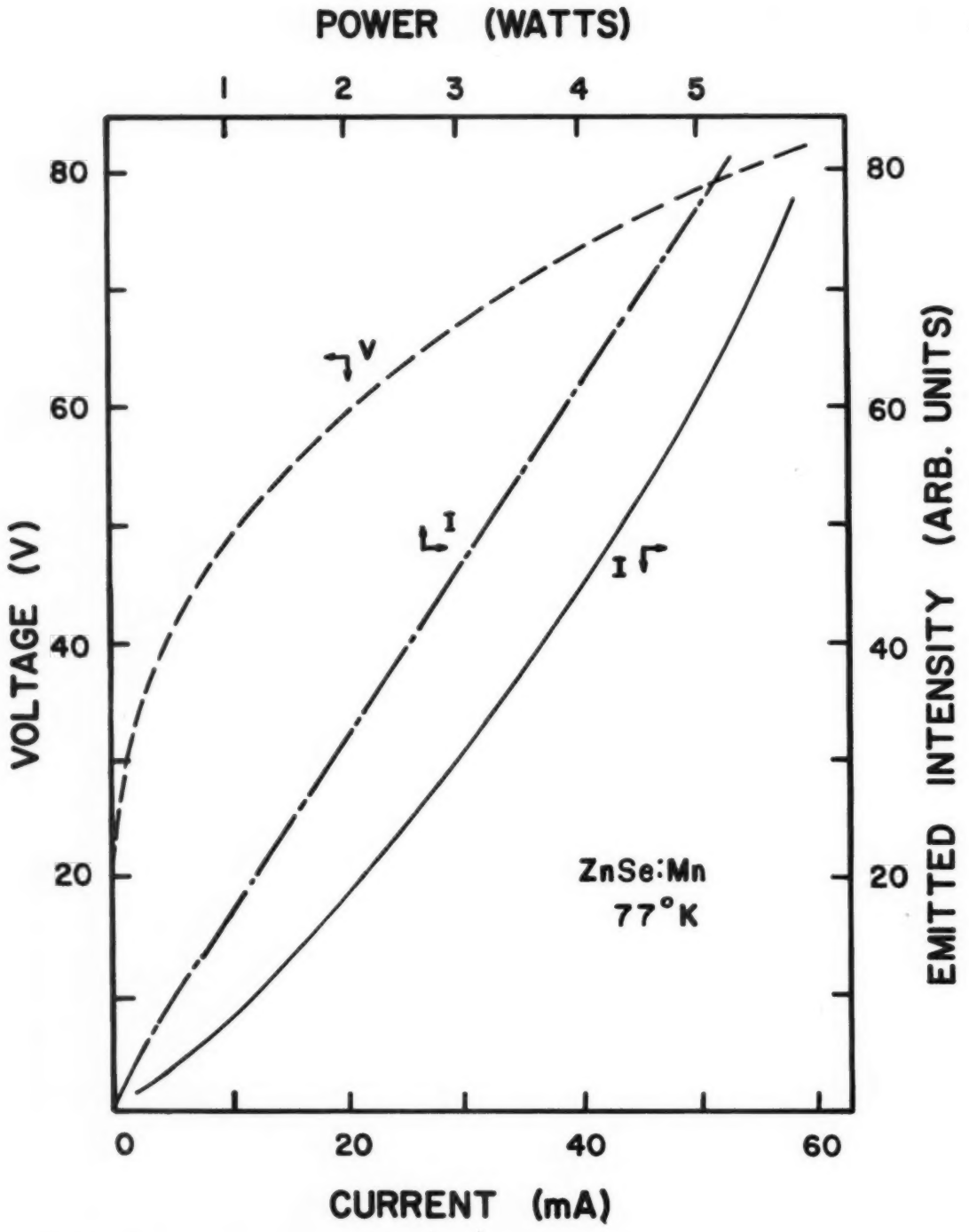


Fig. 3. Dashed Line: Voltage-current characteristic. Solid Line: Emitted intensity as function of injection level. Dot-dash Line: Emitted intensity as function of input power.

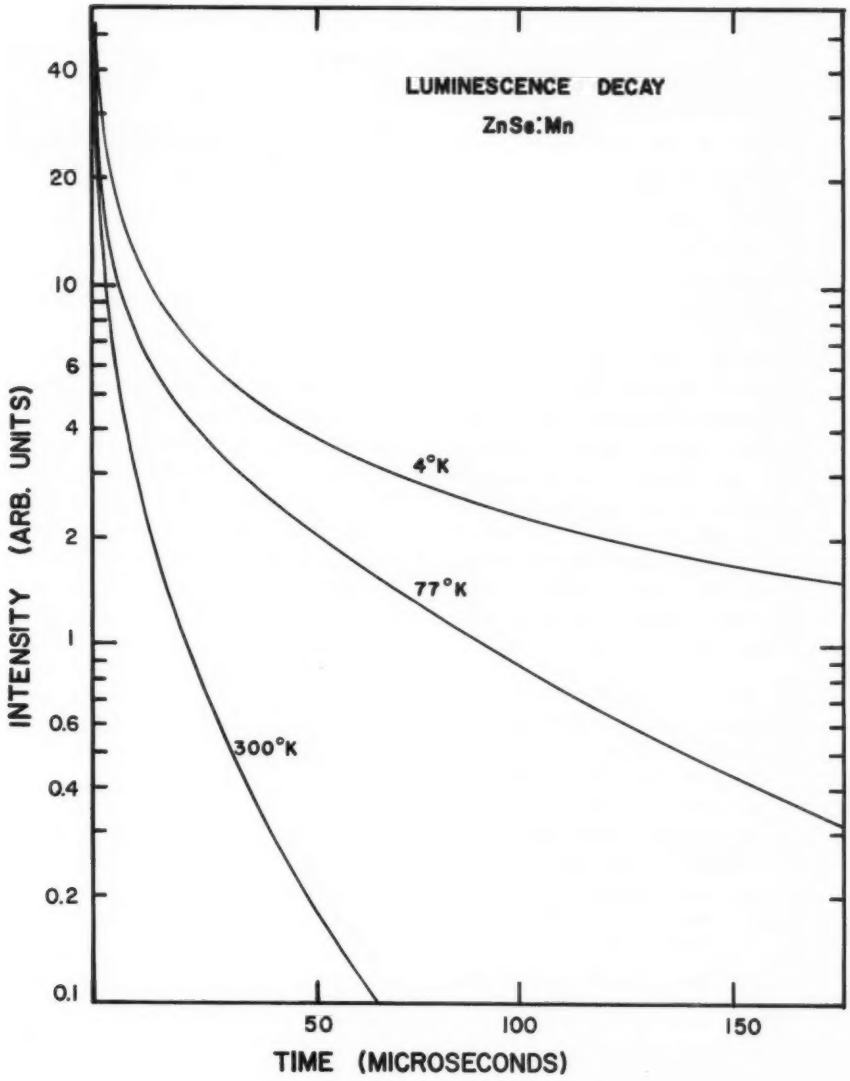


Fig. 4. Decay of the luminescence of ZnSe:Mn at different temperatures.

spectral distribution of the Mn emission was observed at points on the p-type contact at voltages as low as 20 volts across a 5 mm-wide crystal. The intensity of this light, as a function of injected carriers, is plotted as the solid curve in Fig. 3. When plotting the total intensity as a function of input power, a linear relation was found (dot-dash line in Fig. 3). Unfortunately, the p-type contact usually deteriorated with higher injection current densities. The calculated quantum efficiency was 10^{-4} when measurements were made on an approximately parabolic sample with a p-type contact of about 0.5 mm^2 area. Measurements at room temperature gave an efficiency of about one order of magnitude lower. Different arrangements of p-type contacts, such as electroplated Cu, were also used, but without consistent improvement. The efficiency increased with increasing Mn content, up to a concentration of 1.5% Mn. The more highly activated crystals had lower efficiencies and were not as perfect in appearance.

maneuvers--or take offensive action against the source of ground fire--as soon as he knows he's being shot at. The concept was conceived and largely developed by Dr. Philip Lieberman.

The system consists basically of two microphones, positioned beneath the helicopter (or aircraft), and a high-pass filter. Figure 2 shows the main components of the prototype. Critical to the system is the use of an artificial head. The microphones are mounted in either side of this head, thus simulating human ears. (Actually a teardrop configuration for the head has proved most effective.) The signal from each microphone is channeled separately to each phone of the pilot's binaural headset. This gives the pilot natural directional information.

Signals received by these microphones are high-pass filtered at 3.5 kc. The filtering removes the major frequency components of the helicopter noise, leaving half of the sound energy of gunfire, which is then amplified. This amplification enhances the gunfire signal-to-noise ratio approximately 30 db for most helicopter and certain fixed-wing aircraft.

Through either electronic or acoustic mixing, the pilot and air crew can monitor the ground-fire detector and the aircraft intercom simultaneously. Electronic mixing involves channeling both inputs into a single binaural headset. Acoustic mixing involves the wearing of two headsets and requires no modification of existing equipment. To monitor the ground-fire detector by the latter method, the user inserts into his ears small binaural phones of the hearing-aid type, and wears an intercom headset or a normal flying helmet over them.

The detection system has been tested in an H-13 helicopter, a C-47, and liaison aircraft at Fort Devens, Mass., Eglin AFB, Florida, and at Camp Edwards, Mass. It was found that the position of a 7.62-mm machine gun firing short bursts of live ammunition could be located from the helicopter at altitudes that ranged from 100 to 400 feet,

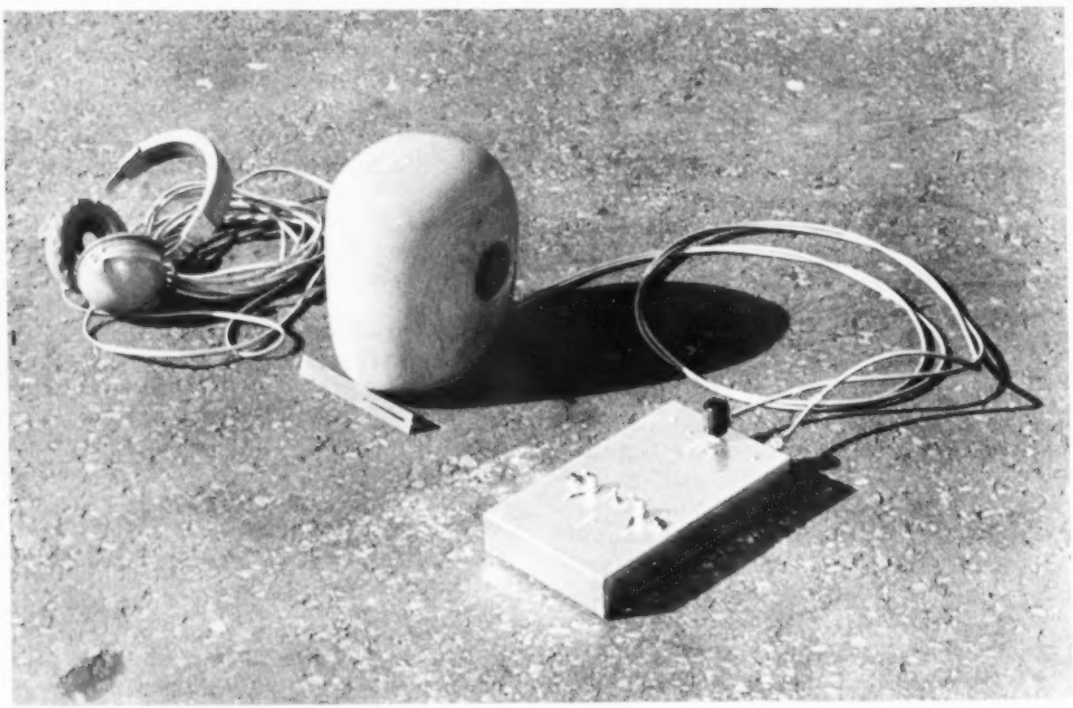


Fig. 2. First prototype of ground-fire detector. Left to right: binaural headset; aerodynamic head containing two microphones, one on either side; and control unit.

and at distances up to 200 yards during normal combat maneuvers. Figure 3 shows the detector head installed on an HU-1B helicopter.

The detection system is rugged, self-powered, and uncomplicated. Its electronic components can be miniaturized to less than 10 cubic inches, if desired. The system can be produced at a cost less than $100 per unit. It will be especially useful for helicopters, C-47s, and forward air-controller aircraft. It should prove to be of value in almost any aircraft engaged in low-level flight over hostile forces.

The system was conceived, designed and built, laboratory-tested, and field-tested within the remarkably short period of two months. ★

Fig. 3. Ground-fire-detector head installed under nose of HU-1B helicopter.

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